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ESTIMATES OF GROUND MOTION AT MINUTEMAN MISSILE SITES FROM TWO LARGE 1979 EARTHQUAKES

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The ground motion caused by the February 28, 1979, St. Elias, Alaska, and March 14, 1979, Petatlan, Mexico, earthquakes is estimated at the MINUTEMAN missile sites in the central United States. The estimates are made by obtaining recordings of the ground motion at other locations in the United States and correcting these recordings to be appropriate for the ranges and azimuths of the MINUTEMAN installations. The ground motion from the two earthquakes
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20. ABSTRACT (continued)

was very large ($M_S \geq 8.0$) in the central United States and most recordings were off-scale. The most useful records were from Wood-Anderson seismometers, especially from two stations in Utah.

The dominant motion is due to surface waves with periods of 10 to 20 seconds. Theoretical considerations supported by teleseismic observations of these events and central United States observations of some large aftershocks suggest that the range and azimuth differences between the Utah Wood-Anderson seismometers and the MINUTEMAN sites do not have a strong effect on the ground motions. Comparing recorded motions from several seismometers in the western United States, we also obtain some idea of the possible effect of local structure variations.

The ground motion estimates are presented in the form of standard five percent damped response spectra. At three seconds the response spectra are about the same (within a factor of two or three) at all the MINUTEMAN sites. For the Mexican event these estimates are 0.05 cm (relative displacement), 0.1 cm/sec (pseudo-relative velocity), and 0.002 cm/sec^2 (absolute acceleration). For the Alaskan event, the estimates are about half as large. These estimates are essentially the same as those given by Rodi, et al. (1970) for the Wing 5 motions due to the 1975 Pocatello Valley earthquake, using synthetic seismogram methods.

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I. INTRODUCTION AND SUMMARY

The objective of this project was to estimate the ground motion at the Minuteman missile sites in the central United States due to the M_s 7.1 St. Elias (Alaska) earthquake of February 28, 1979 and the M_s 7.6 Petatlan (Mexico) earthquake of March 14, 1979. In most of the report we refer to these as the "Alaskan" and "Mexican" earthquakes. Of special interest is the standard response spectrum computed from the ground motion, particularly at periods near three seconds.

Accomplishing the objective of this project required the collection of data from all available sources and the analysis of these data. Data collection proved to be difficult because of the large size of the earthquakes. Almost every record in North America was off-scale. The best records proved to be from a few Wood-Anderson seismometers in the western United States. The Wood-Anderson records collected by the University of Utah were especially useful because of their low gain and proximity to several of the missile installations. In addition to collecting seismograms, we also compiled reported magnitude measurements and some aftershock recordings to provide supplementary information for our ground motion estimates.

The first step in analyzing the data was to digitize the seismograms and prepare them for further processing. The instrument response was deconvolved from the seismograms and the "true" ground motion was then used to compute standard response spectra at the recording sites. Corrections were then made for range, azimuth and location differences to estimate the ground motion at the missile sites.

The ground motion in the central United States was quite large, with an apparent magnitude (M_s) of near 8.0 for both earthquakes. This is much larger than the worldwide average M_s values of 7.1 (Alaskan) and 7.6 (Mexican) reported by the U. S. Geological Survey (USGS). The ground motion was dominated by surface waves which had maximum ground displacements of slightly less than one centimeter.

The large distance from the earthquakes to the central United States and the low frequency character of the dominant amplitude waves should make the ground motion relatively insensitive to local structure and source radiation pattern. Therefore, the range of uncertainty in our estimates is fairly small, probably no more than a factor of three. The estimated ground motions in the central United States were quite similar for the two earthquakes. The values at three second periods from our estimated five percent damped response spectrum at a range of 25° from the Mexican earthquake are 0.05 cm for relative displacement, 0.1 cm/sec for pseudo-relative velocity and 0.02 cm/sec^2 for absolute acceleration.

It is interesting to note that these values are almost the same as the theoretical estimates for the same quantities at Wing 5 (southeastern Wyoming) due to the M_s 6.0 1975 Pocatello Valley, Idaho earthquake by Rodi, et al. (1979).

The three second response spectral amplitudes for the Alaskan earthquake are about half those for the Mexican event. The 25° range is at the near side of the span of ranges for the missile sites. Attenuation causes a decrease in amplitude of less than a factor of two over the entire span of ranges.

II. THE EARTHQUAKES

The two earthquakes to be studied are the February 28, 1979 Alaskan and March 14, 1979 Mexican earthquakes (Table 1). The Alaskan earthquake occurred in the transition zone between the Fairweather (transform) fault, which parallels southeast Alaska, and the Aleutian subduction zone (Lahr, et al., 1979). The Mexican earthquake occurred in the subduction zone along the southwest coast of Mexico (Meyer, et al., 1979).

Both earthquakes produced larger surface waves in the direction of the central United States than were produced in other directions. The average reported surface wave magnitudes for the Alaskan and Mexican earthquakes were 7.1 and 7.6, respectively, but magnitudes of 8.0 or higher were reported in this direction. The distance and azimuth for each of the Minuteman Wings are given in Table 2. The azimuths ranged from 97° to 113° for the Alaskan event, and from 347° to 16° for the Mexican event. Table 3 gives the surface wave magnitudes reported at stations having comparable azimuths. Reported magnitudes of the Mexican event are clearly above average at these azimuths. Data on the Alaskan earthquake are sparse, but two central United States stations at Golden, Colorado, and Albuquerque, New Mexico, reported surface wave magnitudes of 8.1 and 8.0, respectively. Records we have obtained from Dugway and Price, Utah, also show large amplitude surface waves.

The two earthquakes produced very similar ground motion in the central United States. The Minuteman missile sites are located about 25° from both earthquakes. The surface wave magnitude was approximately 8.0 and the body wave magnitude was approximately 6.5 in the region for both earthquakes. From this information alone we can make a crude estimate of ground motion, using the standard magnitude formulas. For the surface waves this is

TABLE 1

EARTHQUAKE STATISTICS (FROM USGS EARTHQUAKE DATA REPORTS)

	Alaskan	Mexican
Date	February 28, 1979	March 14, 1979
Location	60.64N 141.6W	17.81N 101.3W
Origin Time	21:27:06	11:07:16
m_b	6.4	6.5
M_s	7.1	7.6
Depth	15 km	48 km

TABLE 2

DISTANCE AND AZIMUTH TO MINUTEMAN WINGS

	Alaskan		Mexican	
Sites	Distance (degrees)	Azimuth	Distance (degrees)	Azimuth
Wing 1	22°	113°	31°	347°
Wing 2	28°	108°	26°	357°
Wing 3	26°	100°	31°	0°
Wing 4	37°	104°	22°	16°
Wing 5	30°	113°	24°	355°
Wing 6	28°	97°	30°	5°

TABLE 3

REPORTED M_S AT COMPARABLE AZIMUTHS (FROM USGS EARTHQUAKE DATA REPORTS)

ALASKA

Station	ϕ	Δ	T_s	M_s
SJG	93	67	21	7.3
GLD	116	31	18	8.1
ALQ	123	34	20	8.0
BKS	143	26	20	7.1
SPA	180	150	20	8.1

MEXICO

Station	ϕ	Δ	T_s	M_s
BKS	322	27	20	7.6
YSS	322	94	22	7.6
DMR	334	55	20	7.5
ILT	337	69	18	8.1
GLD	352	22	19	7.7
KHE	3	81	16	8.5
SVE	10	104	18	7.9
PUL	22	93	24	7.9
OBN	23	99	22	8.0
MAK	24	113	25	7.8
AKU	26	71	19	8.0
HFS	27	86	20	7.8
GRS	27	115	18	7.6
KRV	27	114	20	7.4

$$M_s = \log \frac{A}{T} + 1.66 \log\Delta + 6.3, \quad (1)$$

where A is the zero-to-peak amplitude in mm at the period T. For $M_s = 8.0$ and $\Delta = 25°$, the amplitude of the 20 second surface wave is about 0.5 cm. Similarly, for one second body waves,

$$m_b = \log \frac{A}{T} + B \ , \quad (2)$$

and $B = 9.5$ for $\Delta = 25°$. Then for $m_b = 6.5$, the one second amplitude is about 1 μm. Clearly, the surface wave will dominate the motion, even at relatively short periods.

III. DESCRIPTION OF DATA AND RECEIVING STATIONS

The two earthquakes were large enough to send most of the seismometers in the United States off-scale, so there are very little data available in the region of interest. All of the WWSSN stations and most other networks were off-scale. Fortunately, there were a few low gain instruments operating during both earthquakes.

The best records we found are from an array of Wood-Anderson seismometers maintained by the University of Utah. The simple, broad response and low gain of the Wood-Andersons makes them ideal for this study. This response is shown in Appendix A (Figure A.1). The Utah stations are DUG at Dugway, Utah, and PCU at Price, Utah. The locations of these stations are given in Table 4. The azimuths of the stations are close to the azimuths of the Minuteman Wings for both earthquakes. Furthermore, the travel path to Utah is similar (continental) to the travel paths to the Minuteman Wings. The ground motion at the Minuteman sites should, therefore, be similar to the ground motion in Utah. Differences are expected from attenuation, local structure and the source radiation pattern.

Two other sets of Wood-Anderson seismograms were obtained. One set came from the Byerly (BKS) station maintained by the University of California at Berkeley. The other sets came from the Cal Tech-USGS southern California network. The stations from this network used in this study are CWC, RVR and TIN. The travel path to BKS and RVR is more complex than the travel path to Utah, since it lies along the plate boundary for both earthquakes and is neither strictly oceanic or continental. This is probably the reason the surface waves are more dispersed and lower in amplitude. The travel paths to TIN and CWC are more confined to the continent and in this sense are more similar to those to the central

TABLE 4

RECEIVING STATIONS

Station	Location	Latitude	Longtitude	Instrument
BKS	Berkeley, CA	37°52.60'	122°14.1'	Wood-Anderson
CWC	Cottonwood Creek, CA	36°26.35'	118°04.68'	Wood-Anderson
DUG	Dugway, Utah	40°11.70'	112°48.80'	Wood-Anderson
PCU	Price, Utah	39°36.40'	110°48.30'	Wood-Anderson
PWY	Pinedale, WY	42°46.67'	109°33.33'	KS36000 (SP)
RVR	Riverside, CA	33°59.6'	117°22.5'	Wood-Anderson
TIN	Tinemaha, CA	37°03.30'	118°13.70'	Wood-Anderson

United States, but they do cross quite different tectonic provinces. The differences between these stations and the Minuteman sites will include these travel path differences as well as those due to local structure and radiation pattern.

We obtained one other good record from a low gain SDAC station located in Pinedale, Wyoming. This is a high-quality digital recording on a KS36000 short period seismometer (Appendix A, Figure A.3). The rapid decrease in response at long periods makes it difficult to use for accurate estimates of the surface wave amplitudes, but this is the most reliable record for the shorter period body waves.

Some conclusions may be drawn from the raw seismograms. Wood-Anderson recordings from several stations are shown in Figures 1, 2 and 3. In Table 5 are listed the locations of the receiving stations relative to the earthquakes, the maximum amplitudes of the body and surface waves, and the corresponding periods. The motion from the two earthquakes is quite similar at these stations. The maximum displacement is about two millimeters at a period of about 12 seconds at most of the receiving stations. The notable exception to this is the large amplitude motion recorded in Utah for the Mexican earthquake. At DUG this gives an M_s of 8.3.

Another interesting feature of the data is the generation of higher frequency (five to eight second) surface waves of fairly large amplitude at certain locations. The stations TIN and CWC are located about 80 km apart along the Owens Valley to the north and CWC at the south end of the valley. For the Mexican earthquake, TIN shows considerable amplification of short period surface waves compared to CWC, especially in the north-south component. The main surface wave arrival is preceded by a pulse of five second surface waves lasting for two minutes with an amplitude of 0.5 mm. The reason for this is not entirely clear, but may result from a change in

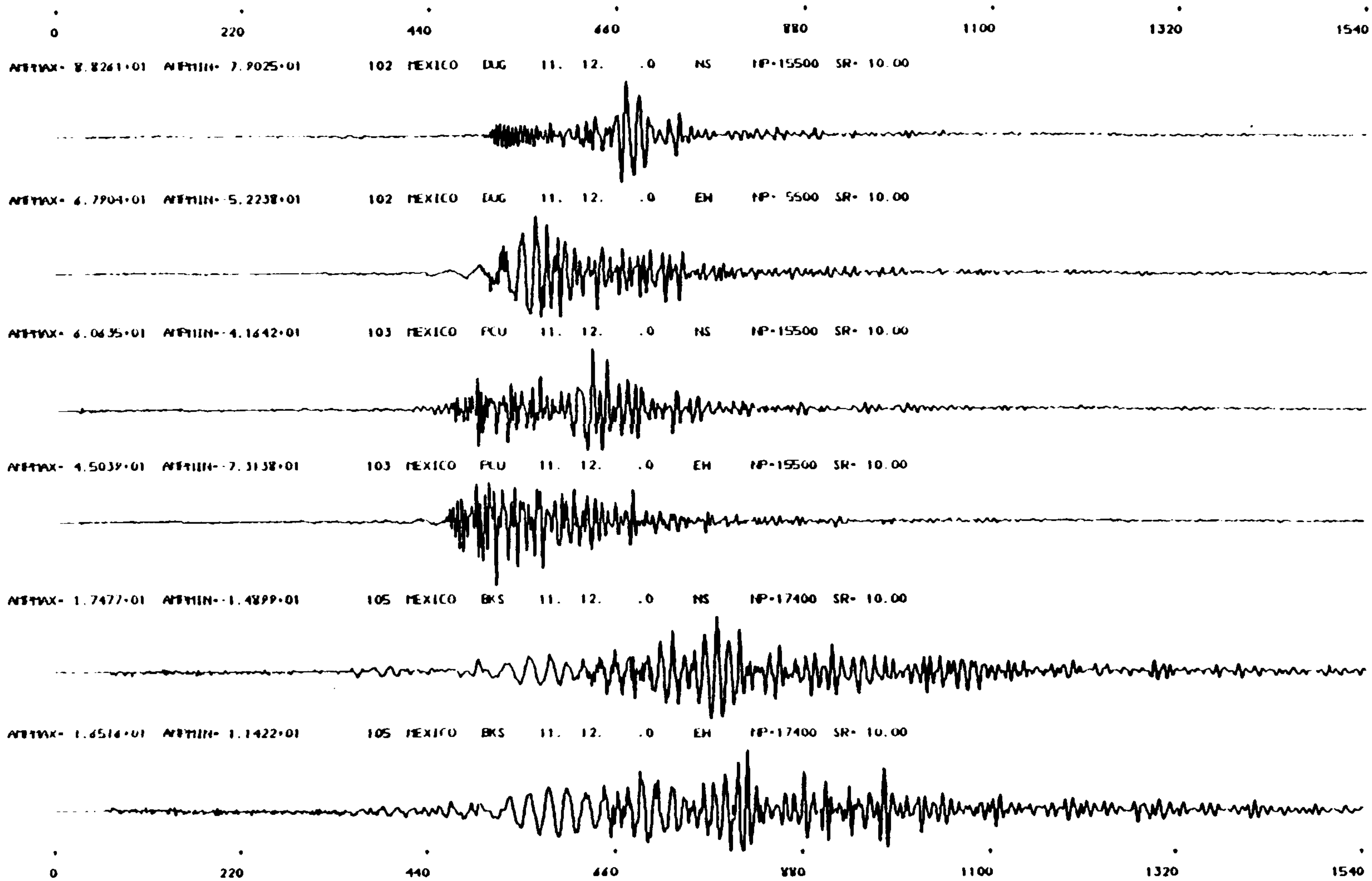

Figure 1. Wood-Anderson seismograms of the Mexican earthquake recorded at DUG, PCU and BKS. Each pair consists of the north-south and east-west seismograms.

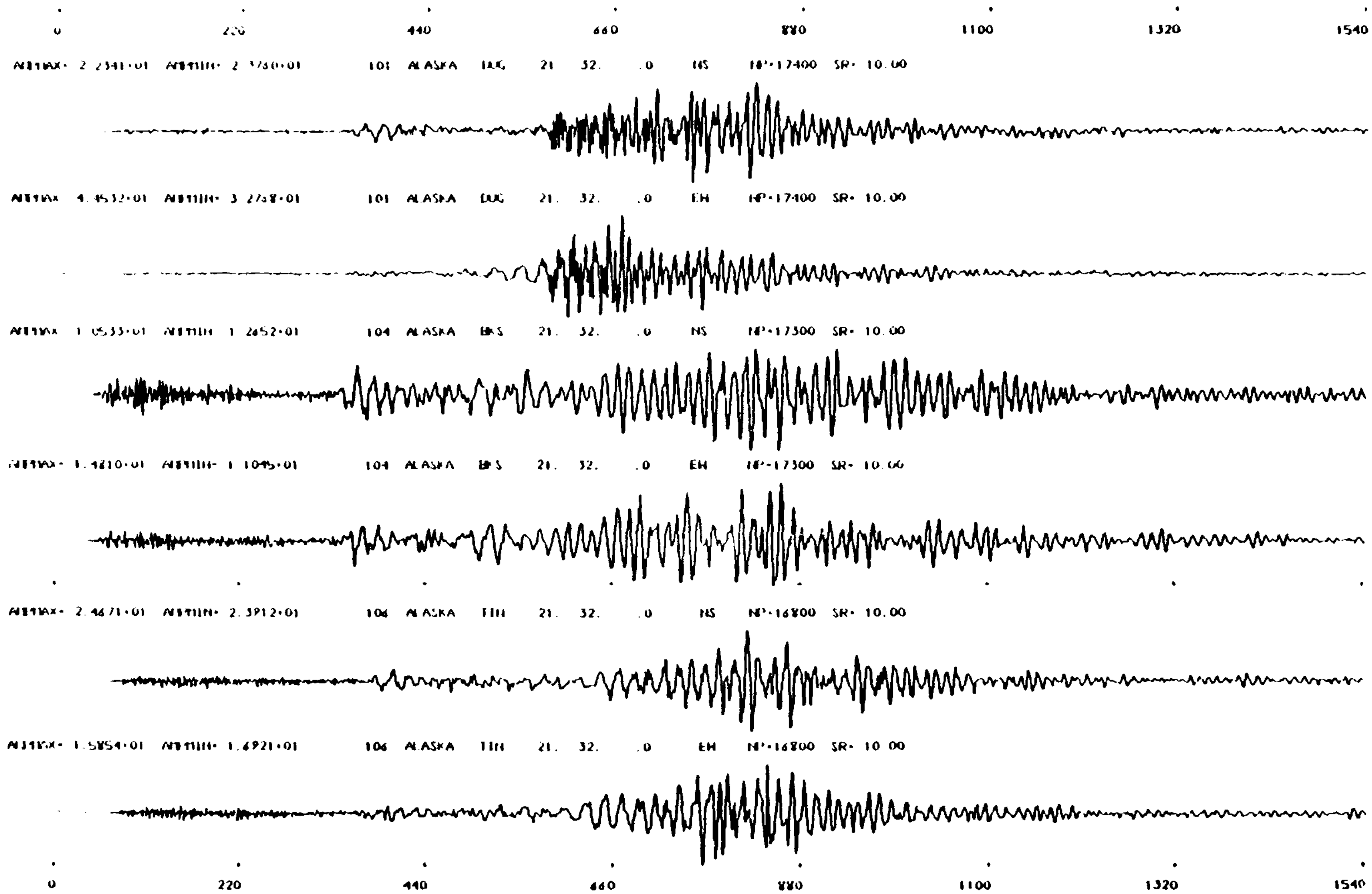

Figure 2. Wood-Anderson seismograms of the Alaskan earthquake recorded at DUG, BKS and TIN.

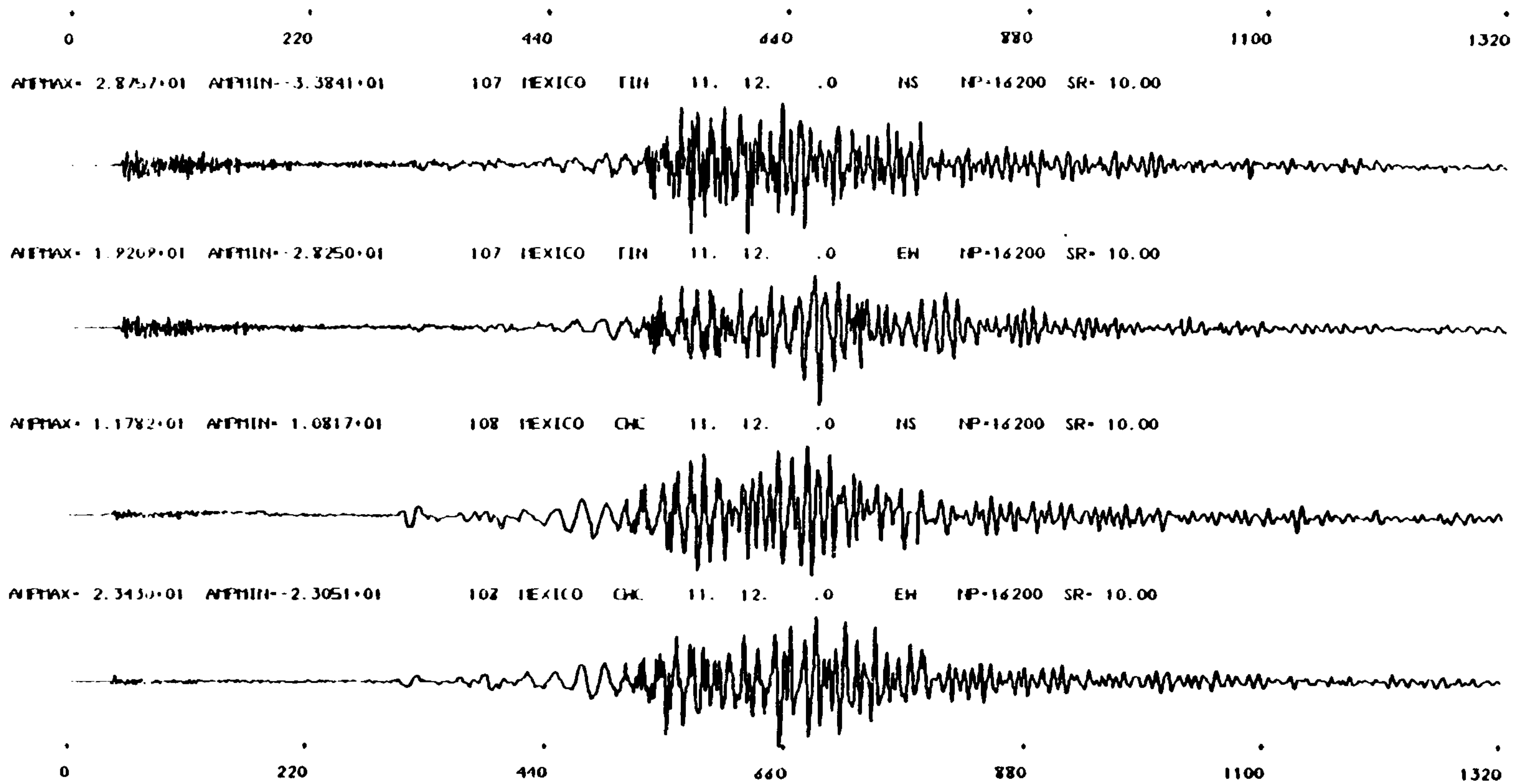

Figure 3. Wood-Anderson seismograms of the Mexican earthquake recorded at TIN and CWC. Note the increased high frequency character of the north-south component at TIN.

TABLE 5

EARTHQUAKE DATA

ALASKA

Station	Δ	ϕ	A_b	m_b	T_b	A_s	M_s	T_s
BKS	25.8	143	0.03	7.1	5	1.4	7.7	13
DUG	27.1	126	0.02	7.1	5	1.7	7.8	12
RVR	30.9	138	0.03	7.4	5	1.2	7.8	11
TIN	27.9	137	0.02	7.3	4	1.8	7.9	12
MEXICO								
BKS	27.1	322	0.01	6.8	5	2.0	7.8	14
CWC	23.8	325	0.03	7.0	5	1.2	7.7	10
DUG	24.4	338	0.04	7.2	5	7.8	8.3	14
PCU	23.2	341	0.04	7.2	5	4.0	8.1	11
PWY	25.9	346	0.007	7.0	2	1.6	7.9	10
RVR	21.6	321	0.02	6.8	5	2.8	7.8	15
TIN	24.3	325	0.04	7.3	4	1.5	7.8	10

$$m_b = \mathrm{Log}\,\frac{A_b}{T_b} + B$$

$$M_s = \mathrm{Log}\,\frac{A_s}{T_s} + 1.66\ \mathrm{Log}\Delta + 6.3$$

A = zero to peak amplitude (mm) at period T.

B = 9.5 at 25°.

the depth of sediments or from "focusing" of surface waves along the narrowing north-south valley.

IV. ANALYSIS

4.1 NUMERICAL RESULTS-RESPONSE SPECTRA AT OBSERVATION POINTS

From the preceding sections we can draw the following conclusions:

1. The ground motion in the central United States was larger than indicated by the worldwide average magnitudes.

2. The ground motion caused by surface waves greatly exceeded the ground motion caused by body waves.

3. The surface wave energy is largest in the 10 - 20 second period range.

4. Local structure can cause surface wave amplification. In particular, shorter period surface waves with fairly large amplitudes are generated at some sites.

In order to get more information about the ground motion, it is necessary to apply numerical techniques to the seismograms. The technique used for the analysis is to first deconvolve the recording instrument from the seismogram over the frequencies of interest, using a causal pseudo-inverse which is described in Appendix B. Response spectra can then be computed from the deconvolved waveforms which represent the "true" ground motion. With the exception of the Pinedale record, our data are all horizontal component (east-west and north-south) seismograms. There is no vertical Wood-Anderson seismometer. The east-west and north-south components are generally similar in amplitude and frequency content. We compute the average response spectrum at each site, rather than attempting to separate out the radial and tangential components. The vertical component response spectra should be very similar.

Figures 4 and 5 show the deconvolved waveforms at several receiver sites. The deconvolution was carried out to 25 second periods. Note the much longer and more dispersed wavetrain observed at Berkeley compared to the Utah stations. We believe this is due to a more complex travel path along the plate boundary, compared to the continental travel path to the Utah stations.

Figures 6 through 10 are response spectra made from the deconvolved waveforms. Since the seismograms were only deconvolved to 25 seconds, the seismograms are inaccurate at longer periods. As a result, the response spectra will be increasingly inaccurate at periods longer than about 25 seconds, but they should be quite accurate at short periods. All response spectra were made using five percent damping and are averages of east-west and north-south response spectra.

It is immediately apparent that the records at the two Utah stations give very similar response spectra, especially at shorter periods. The main difference between them is the larger amount of low frequency response at Dugway. The response spectra from the Berkeley records, on the other hand, are very different. These records are generally lower in amplitude, especially at short periods. As mentioned above, we attribute this to characteristics of the travel path. Since the path to Utah is very similar to the path to the missile sites, the ground motions recorded there give a much better representation of the missile site ground motion than the ground motion at Berkeley.

For the reasons we have outlined, we consider the DUG ground motion (Figures 6 and 9) to provide a first order approximation to the ground motion at the missile sites. Any

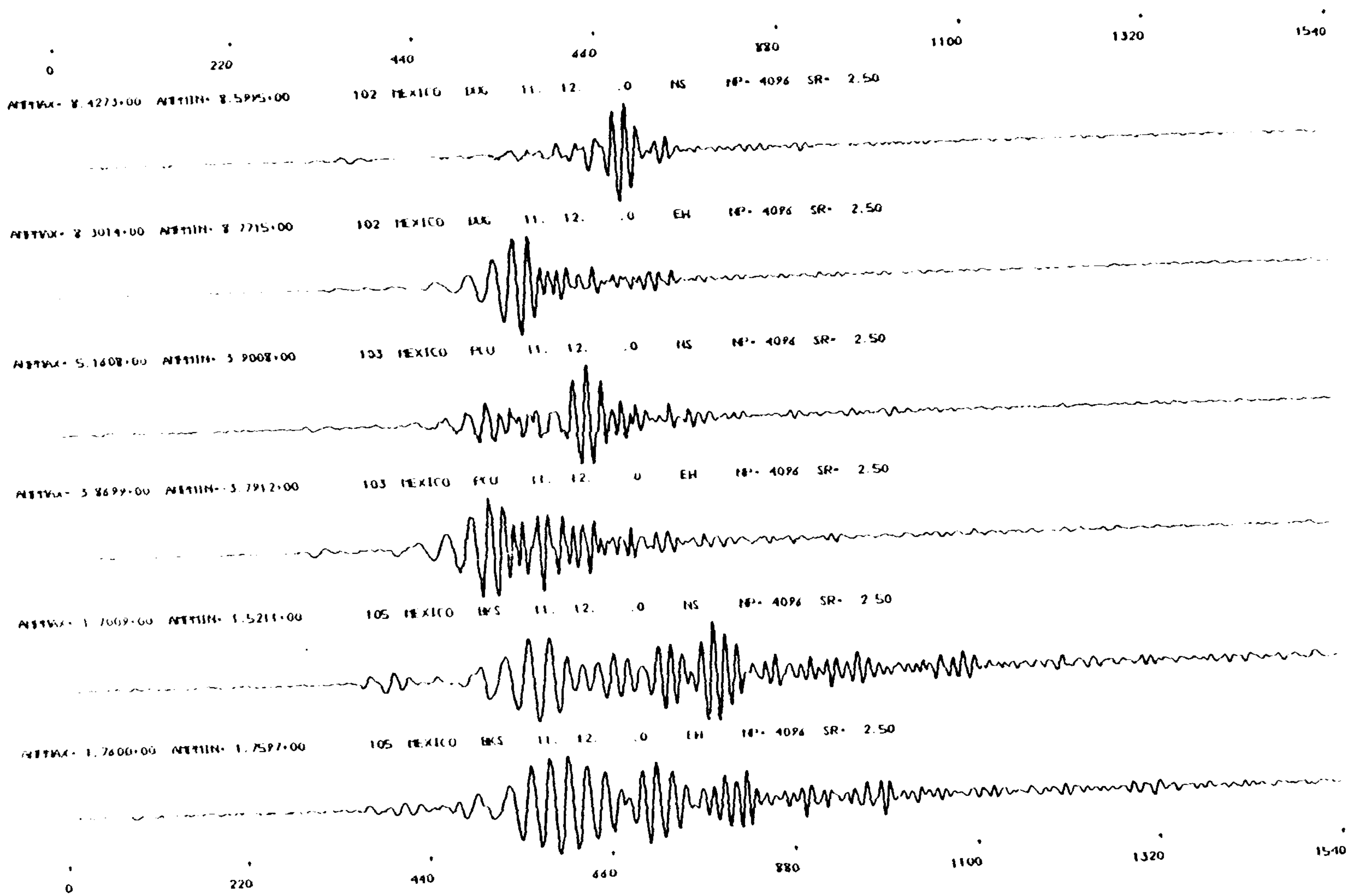

Figure 4. Deconvolved waveforms of the Mexican earthquake.

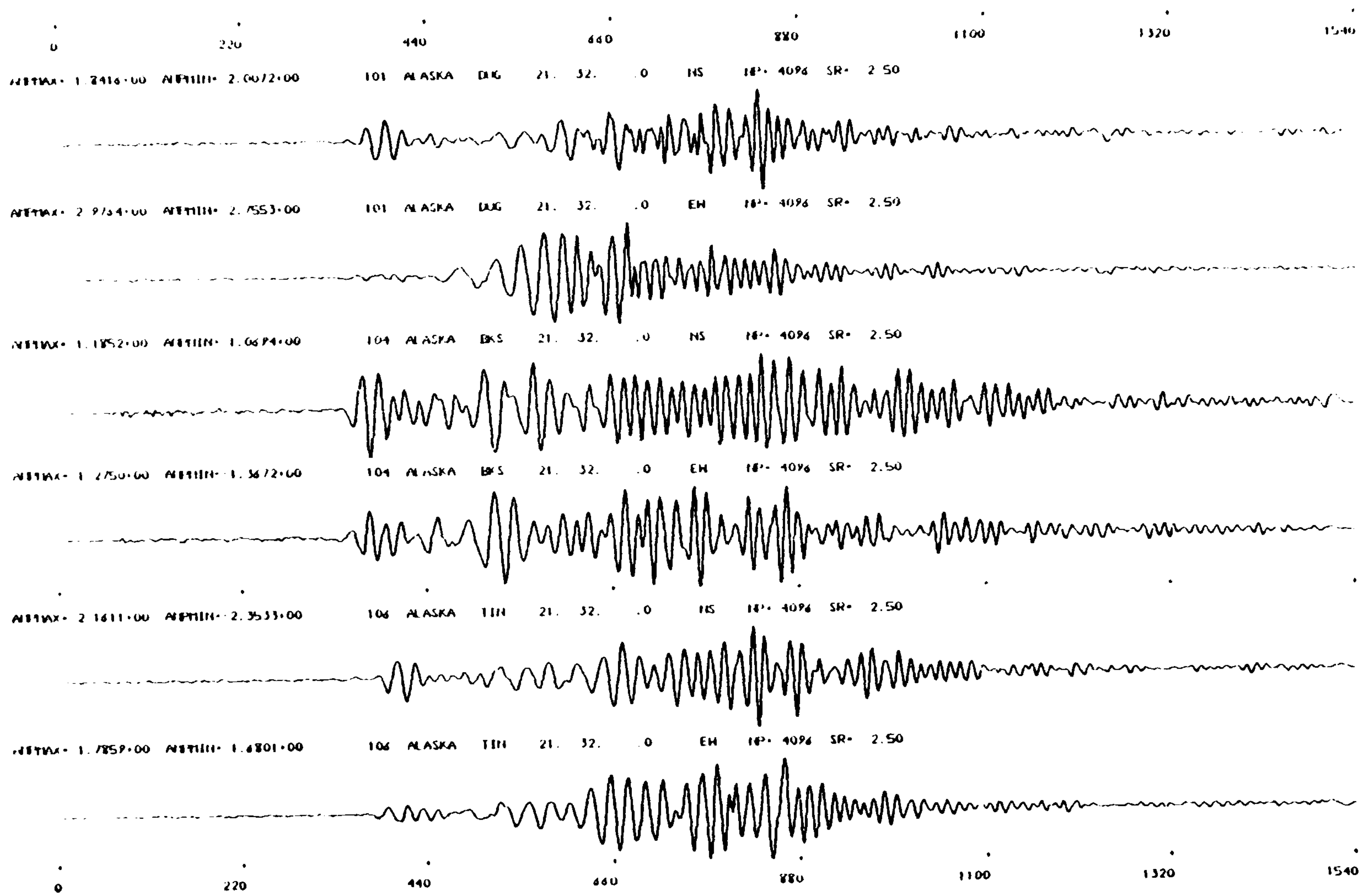

Figure 5. Deconvolved waveforms of the Alaskan earthquake.

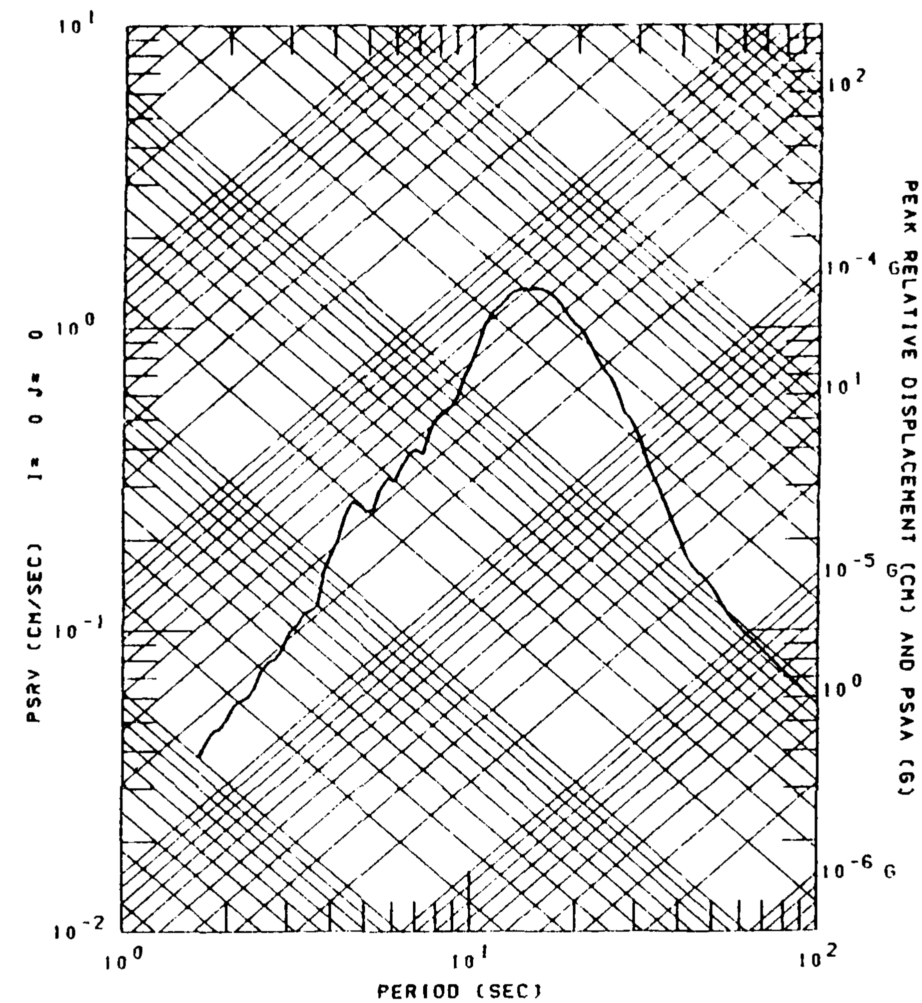

Figure 6. Response spectrum made from the deconvolved waveform at DUG for the Mexican event. This and the following figures are averages of the east-west and north-south response spectra. All have five percent damping.

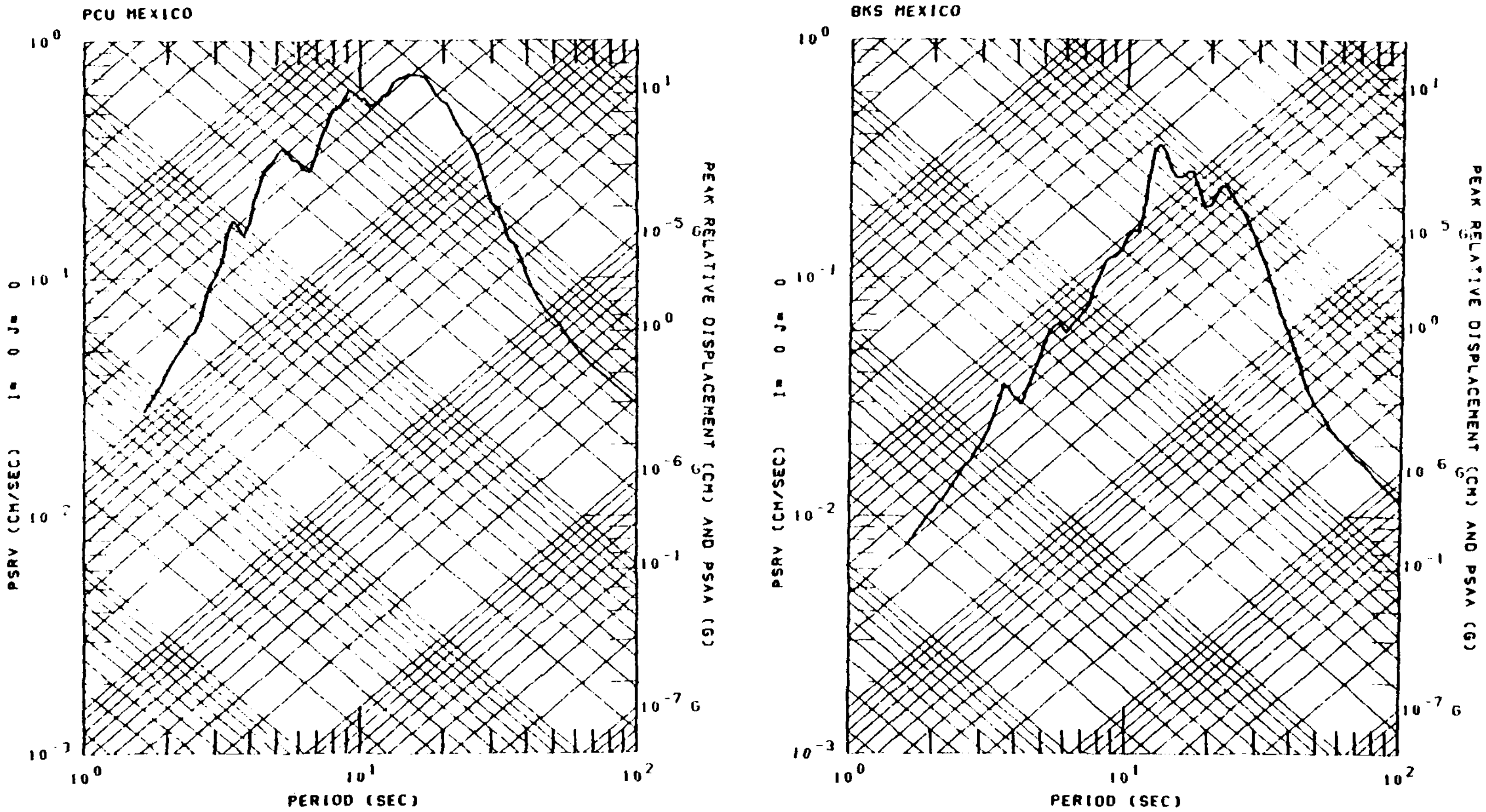

Figure 7. Response spectra of the Mexican earthquake at PCU and BKS. Note the similarity to DUG at short periods on the PCU record. At BKS the amplitude is reduced.

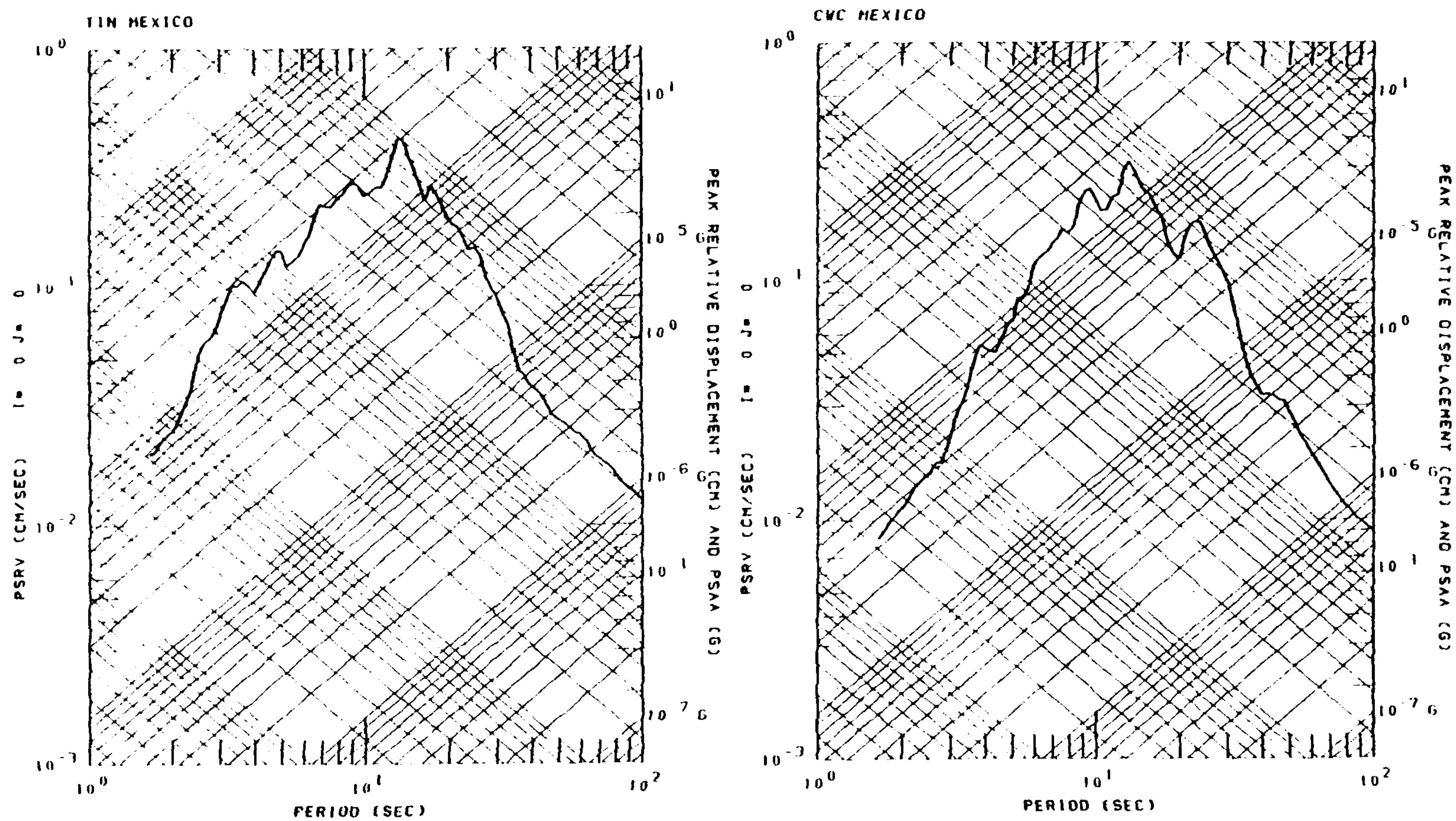

Figure 8. Response spectra of the Mexican earthquake at TIN and CWC. Note the increased short period response at TIN. These stations are quite close to earch other, but the CWC response is more similar to BKS than to TIN.

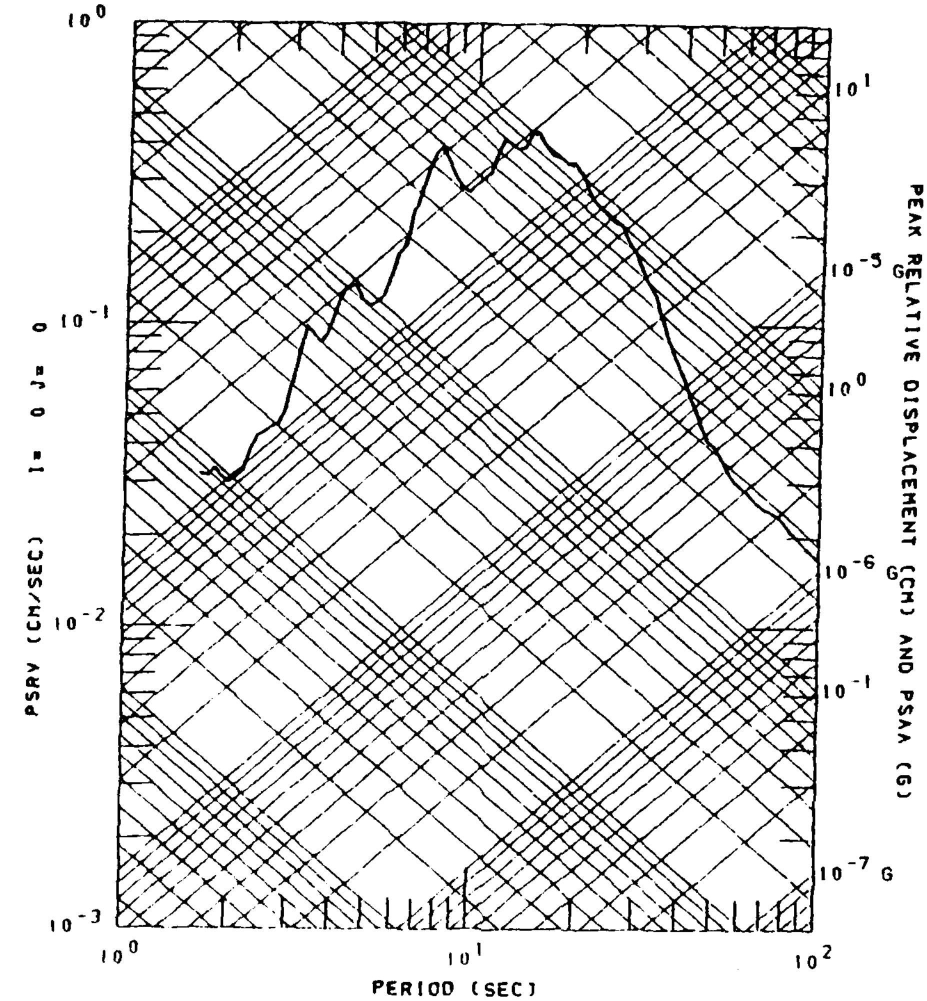

Figure 9. Response spectrum of the Alaskan earthquake at DUG.

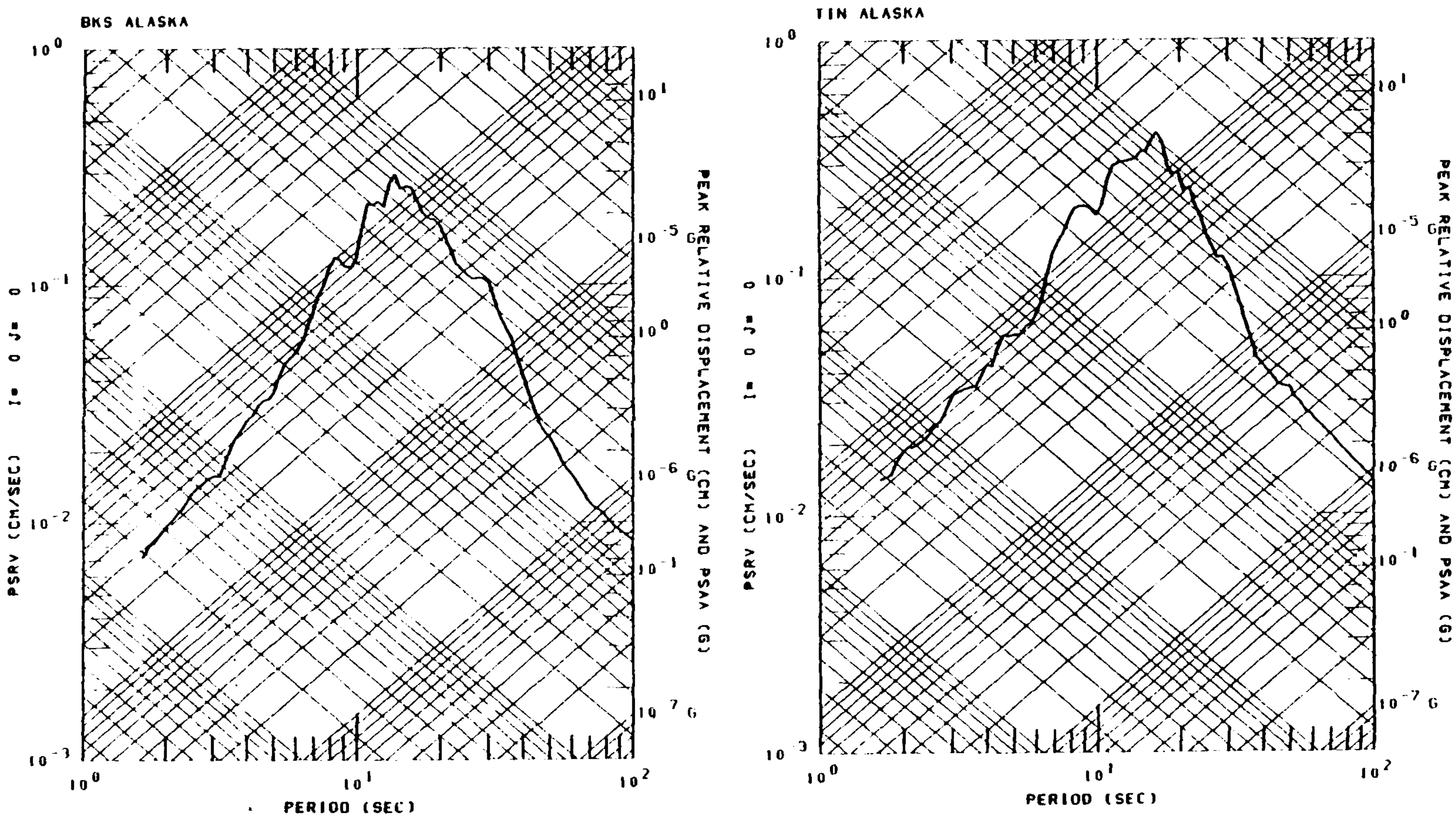

Figure 10. Response spectra of the Alaskan earthquake at BKS and TIN. For this earthquake, the response spectra are very similar at these locations.

differences at the missile sites will be due to:

1. Spreading and attenuation at differing distances.
2. Azimuthal variation due to radiation pattern.
3. Differences in the travel path.
4. Differences in local structure causing local amplification.

All of these corrections are relatively minor and we will attempt to estimate each of them. The values from the DUG response spectrum for the Mexican earthquake at a period of three seconds are:

Relative Displacement = 0.05 cm,

Pseudo-Relative Velocity = 0.10 cm/sec,

Absolute Acceleration = 2.0×10^{-4} g.

For the Alaskan earthquake comparable values are:

Relative Displacement = 0.03 cm,

Pseudo-Relative Velocity = 0.006 cm/sec,

Absolute Acceleration = 1.3×10^{-4} g.

4.2 GROUND MOTION AT THE MISSILE SITES, CORRECTIONS TO THE OBSERVED RESPONSE SPECTRA

4.2.1 Attenuation

To correct the DUG estimates for attenuation, we use empirical estimates for ground motion attenuation in North American. The correction from a station located at Δ_0 to a station at Δ_1 is:

$$A(\omega,\Delta_1) = A(\omega,\Delta_0)\, e^{-\gamma(\omega)\;(\Delta_1-\Delta_0)}\; \frac{\sin^{1/2}\Delta_0}{\sin^{1/2}\Delta_1}\;. \qquad (3)$$

Herrmann and Mitchell (1975) determine average values for $\gamma(\omega)$ for the North American continent. These values, which have rather large error bars, are

$$\gamma(T) \approx 10^{-4} \text{ km}^{-1} , \qquad T > 10 \text{ seconds,}$$

$$\gamma(T) \approx (11 - T) \times 10^{-4} \text{ km}^{-1} , \qquad T < 10 \text{ seconds,}$$

where T is the period and the relative distance in the exponential is in kilometers.

The differential distance between Dugway and the missile sites is less than 10° in every case. Furthermore, most of the energy is at periods longer than ten seconds. Using the listed $\gamma(\omega)$, the correction for attenuation is, therefore, a factor of approximately 0.7. At five seconds this decreases to 0.4.

Figure 11 shows the effect on the response spectrum of applying this attenuation correction for a range difference of 10°. These response spectra were made by filtering the DUG ground motions by (3) with $\Delta_1 = 35°$ and $\Delta_0 = 25°$, and computing the response spectrum from the resulting waveform. The effect is primarily a simple overall decrease in amplitude, with a slightly greater decrease at short periods. At three seconds, the displacement, velocity and acceleration values are all decreased by a factor of 0.5. The approximate attenuation (at three seconds) computed from (3) for each of the missile sites is given in Table 6. This correction is rather small, being much less than a factor of two in all but a few cases.

4.2.2 Radiation Pattern

The source is not known well enough for either earthquake to make an accurate theoretical radiation pattern, but

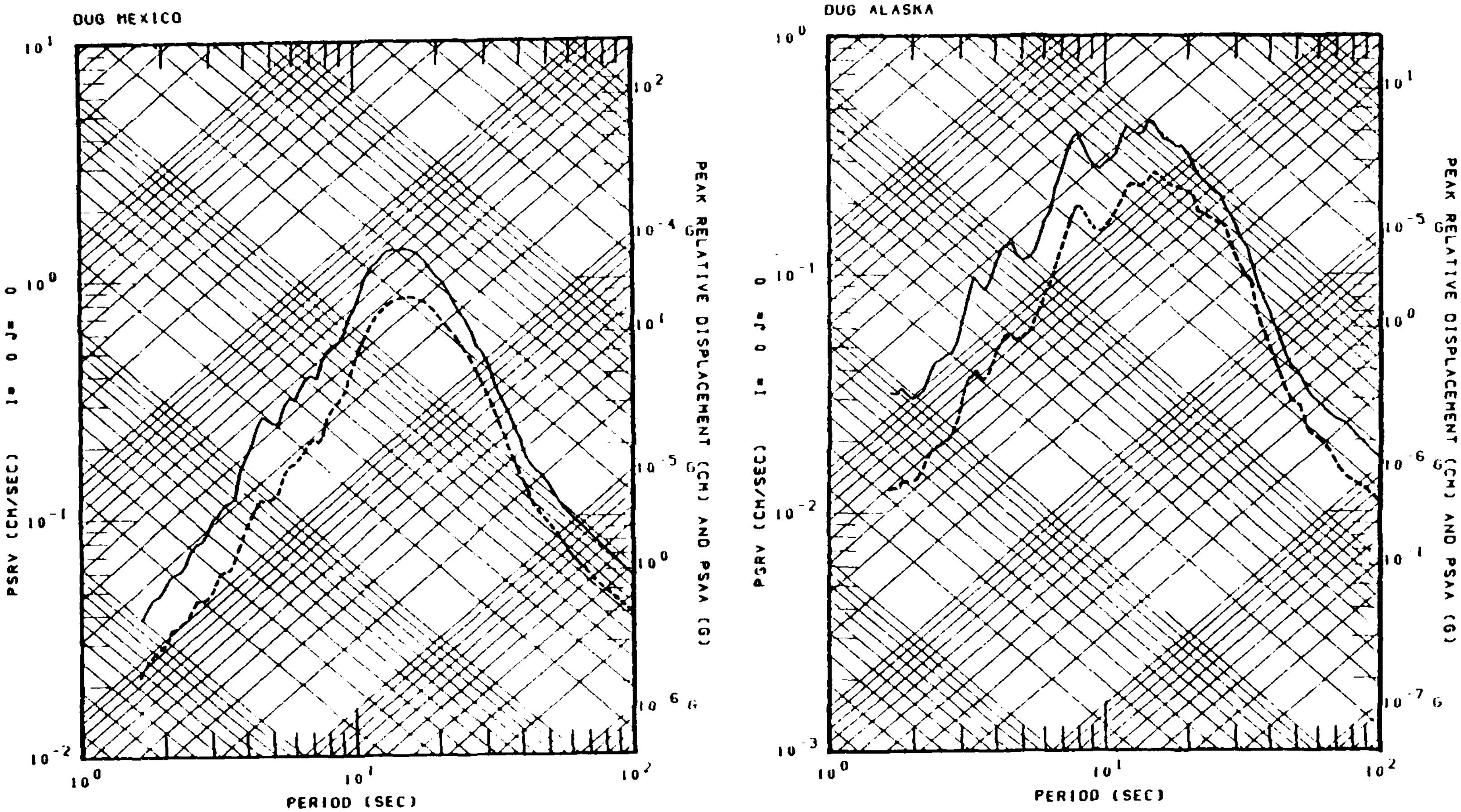

Figure 11. Response spectra corrected for attenuation 10° beyond DUG for the Mexican (left) and Alaskan (right) earthquakes. Attenuation causes a general decrease in amplitude which is slightly greater at short periods. The lower curve shows the attenuated response spectrum.

TABLE 6

ATTENUATION FACTORS FROM DUG TO
THE MINUTEMAN WINGS

	Mexico	Alaska
Wing 1	0.65	1.4
Wing 2	0.90	0.95
Wing 3	0.65	1.1
Wing 4	1.2	0.50
Wing 5	1.0	0.80
Wing 6	0.70	0.95

we can get a rough estimate for the radiation pattern from the recorded magnitudes (Table 3), and our own measurements (Table 5). The question here is whether to expect a large amplitude increase or decrease at the missile site azimuths relative to the Utah measurements. The Mexican event was well recorded at teleseismic distances ($\Delta > 55°$) for the azimuthal sector of the missile sites and shows consistently large amplitudes corresponding to M_s of about 8.0 from $\phi = 335°$ to $\phi = 27°$.

For the Alaskan earthquake, there are much less data near the azimuths of interest, but all continental United States stations reported large amplitudes. A magnitude 5.4 aftershock of the Alaskan earthquake which occurred at 0934 on March 2, 1979, was well recorded by WWSSN stations at Dallas, Texas and Spring Hill, Alabama. These stations are located at azimuths of 114° and 106°, respectively, and are almost identical in amplitude and character. Assuming that the aftershock has the same radiation pattern as the main shock, this indicates that the ground motion was fairly consistent over the azimuths of interest. In conclusion, our analysis, while not conclusive, indicates that there were little ground motion differences due to radiation pattern at the azimuths of interest.

4.2.3 Travel Path and Local Structure

Differences due to travel path and local structure variations cannot be directly determined. However, the similarity of structure along the travel paths and the long distance from the earthquakes to the sites is a good indication that these differences will be minor. Because of the distance to the earthquakes, the range of azimuths at the missile sites (including Utah) is fairly small. The travel paths from both earthquakes to Utah and to all of the missile sites are within the North American continent (Figure 12).

TRAVEL PATHS

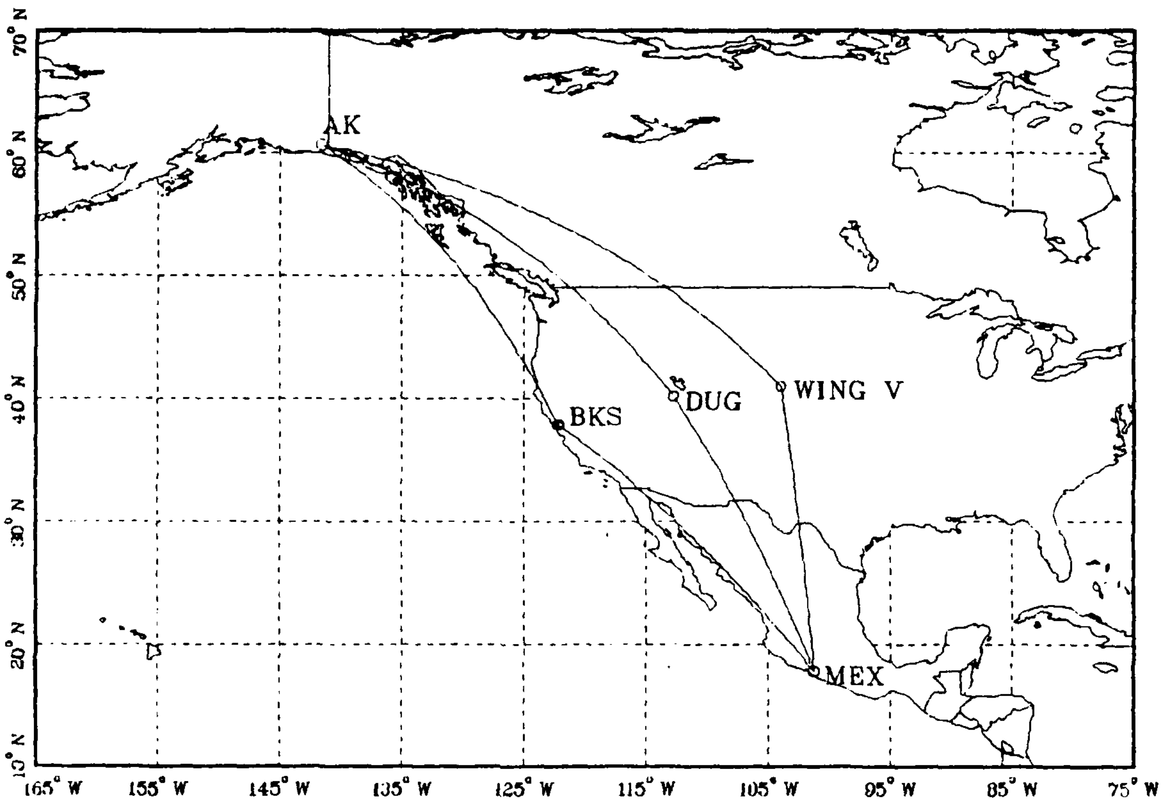

Figure 12. Travel paths of surface waves from the Alaskan and Mexican earthquakes to Wing V and to stations DUG and BKS. The travel paths to Wing V and DUG are continental while the travel paths to BKS run along the plate boundary.

Further, the earthquakes are far enough away that the dominant surface waves are long period and relatively insensitive to variations in structure. The ground motion should, therefore, be quite consistent over the entire region.

An important exception is that local structures or a local travel path can cause amplification of short period surface waves. Figure 8 shows the response spectra of the Mexican earthquake at TIN and CWC. These stations are close to each other, but have very different response spectra. At short periods the response at TIN exceeds the response at CWC by a factor of three. The earthquake was to the south of these stations, and TIN is located at the north end of a long, narrowing north-south valley. It seems likely that the travel path up the valley is responsible for the amplification. It is interesting to note that the response spectrum at BKS is almost identical to the response spectrum at CWC for the Mexican earthquake (Figure 7). We do not have a record at CWC for the Alaskan earthquake, however for this earthquake the response spectra at BKS and TIN are almost identical (Figure 10). If the anomalous response at TIN during the Mexican earthquake were due to local structure, then the ground motion would be expected to be anomalous for the Alaskan earthquake as well. The fact that the anomalous response is seen only for the Mexican earthquake supports the conclusion that the travel path up the valley is responsible for the amplification. A theoretical study of the channeling and amplification of surface wave energy by valleys would be a very interesting future project.

4.2.4 Comparison with Pocatello Valley Earthquake

In a previous study, Rodi, et al. (1979) computed theoretical seismograms for a source model inferred from teleseismic observations (Bache, et al., 1980) to estimate the ground motions at Wing 5 due to the Pocatello Valley earthquake of March 28, 1975. This event was much smaller ($M_s = 6.1$) than the Mexican and Alaskan earthquakes and at a much closer range (700 km). It is interesting to compare the results of the Pocatello Valley analysis with those from this study. The main difference between the response spectra is that those for the Pocatello Valley earthquake peaked at much shorter periods, generally at about three seconds. The ground motion at longer periods is much larger for the Mexican and Alaskan earthquakes than for the Pocatello Valley earthquake. Considering the large magnitude differences between these events, this is about as expected (Eq. (2)). At short periods the ground motions estimated by Rodi, et al. (1979) are about the same as those from the two large events. The Rodi, et al. estimates for the relative displacement is about 0.05 cm, for the pseudo-relative velocity it is about 0.1 cm/sec and for the absolute acceleration it is about 3×10^{-4} g. These are almost identical to the three second estimates for the Alaskan and Mexican earthquakes. The main difference between them is that the high frequency character of the Pocatello Valley ground motion makes it much more sensitive to variations in local structure at the sites and to variations along the travel path.

V. ACKNOWLEDGMENTS

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We also want to thank Bruce Mason and Barbara Flannery for help with a great deal of tedious digitizing and David Lambert for help with the collection of data.

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APPENDIX A

RESPONSE OF INSTRUMENTS USED IN THIS STUDY

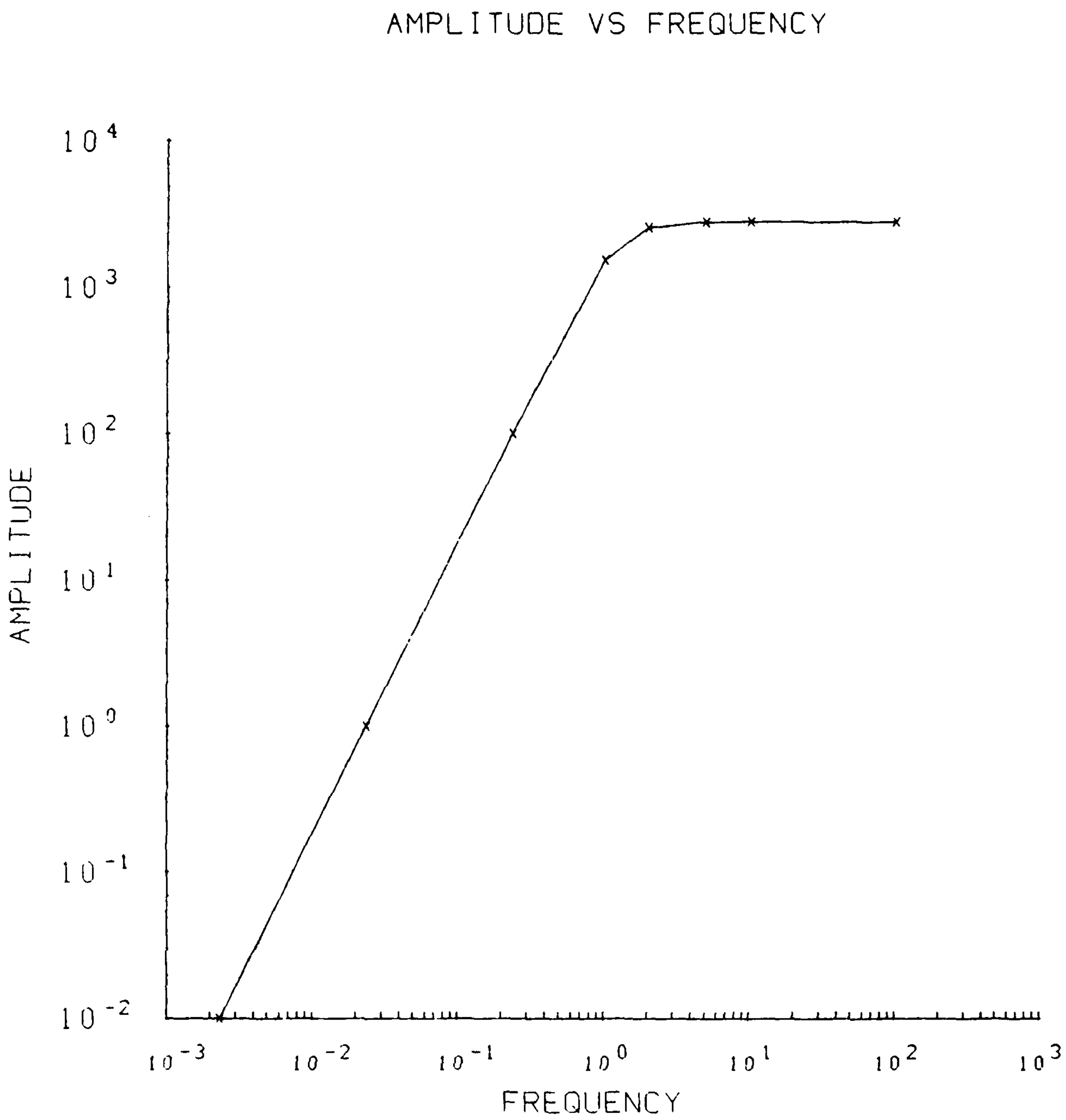

Figure A.1. Amplitude response of the Wood-Anderson seismometer.

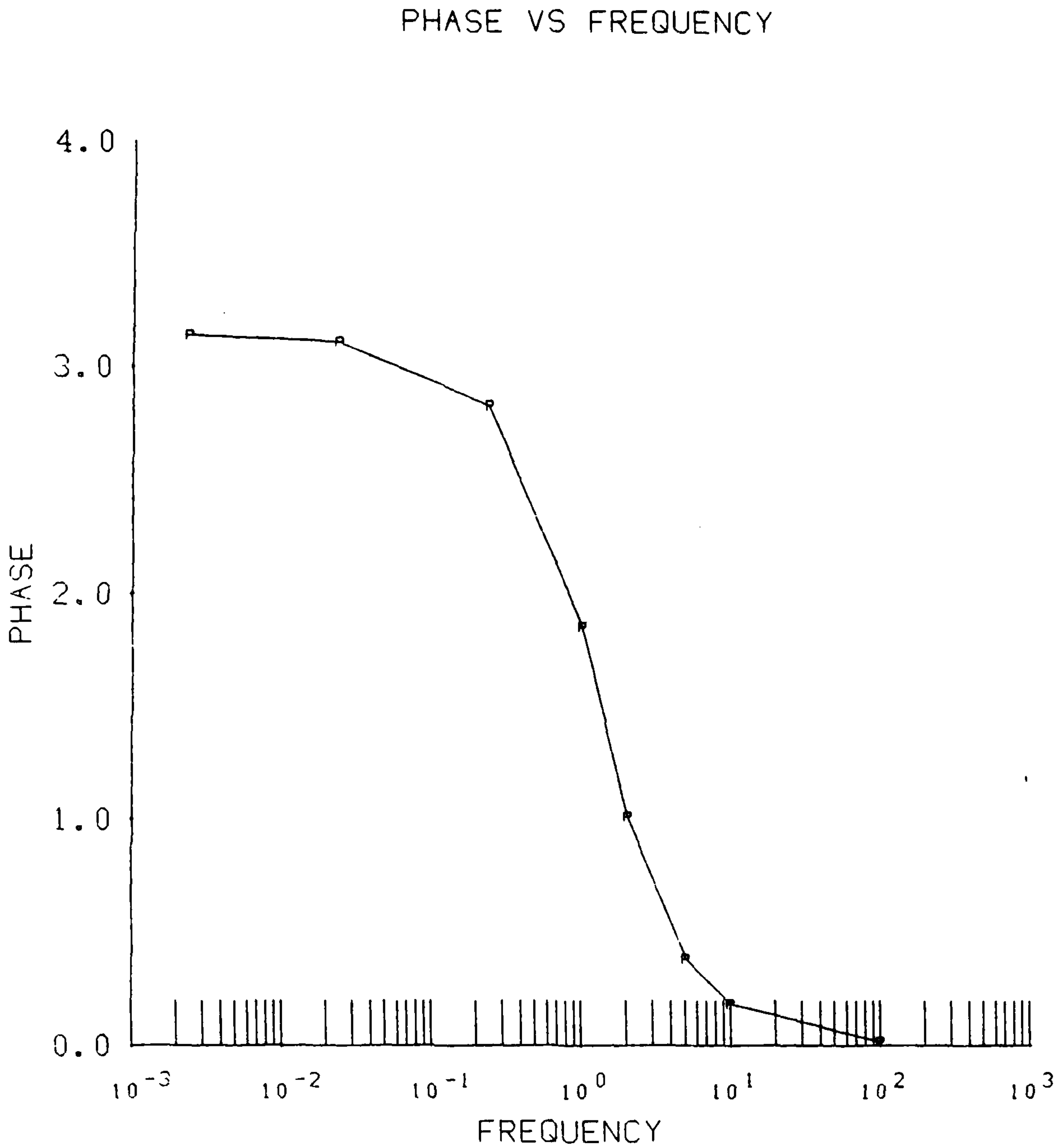

Figure A.2. Phase response of the Wood-Anderson seismometer.

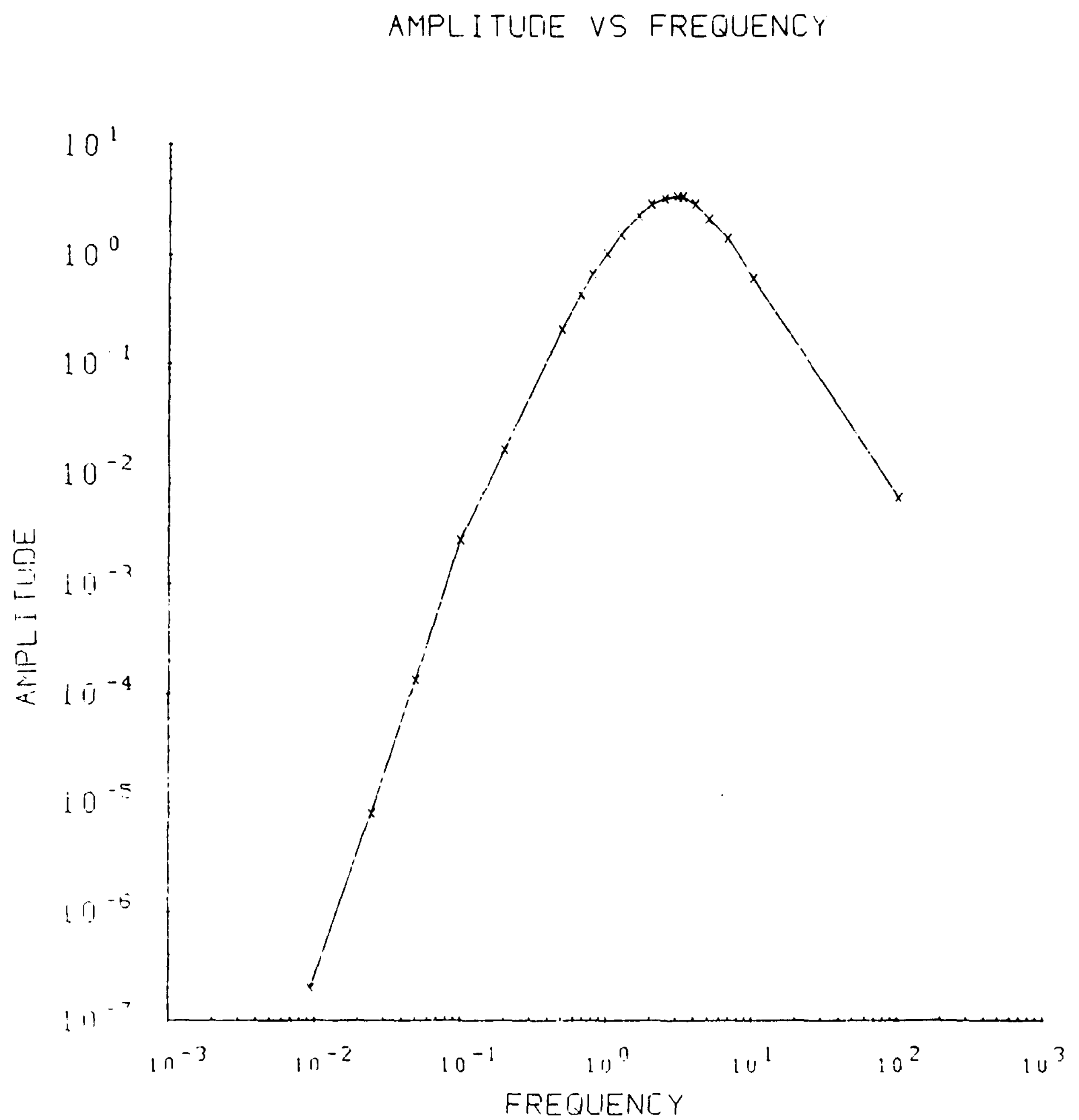

Figure A.3. Amplitude response of KS36000 seismometer at PWY.

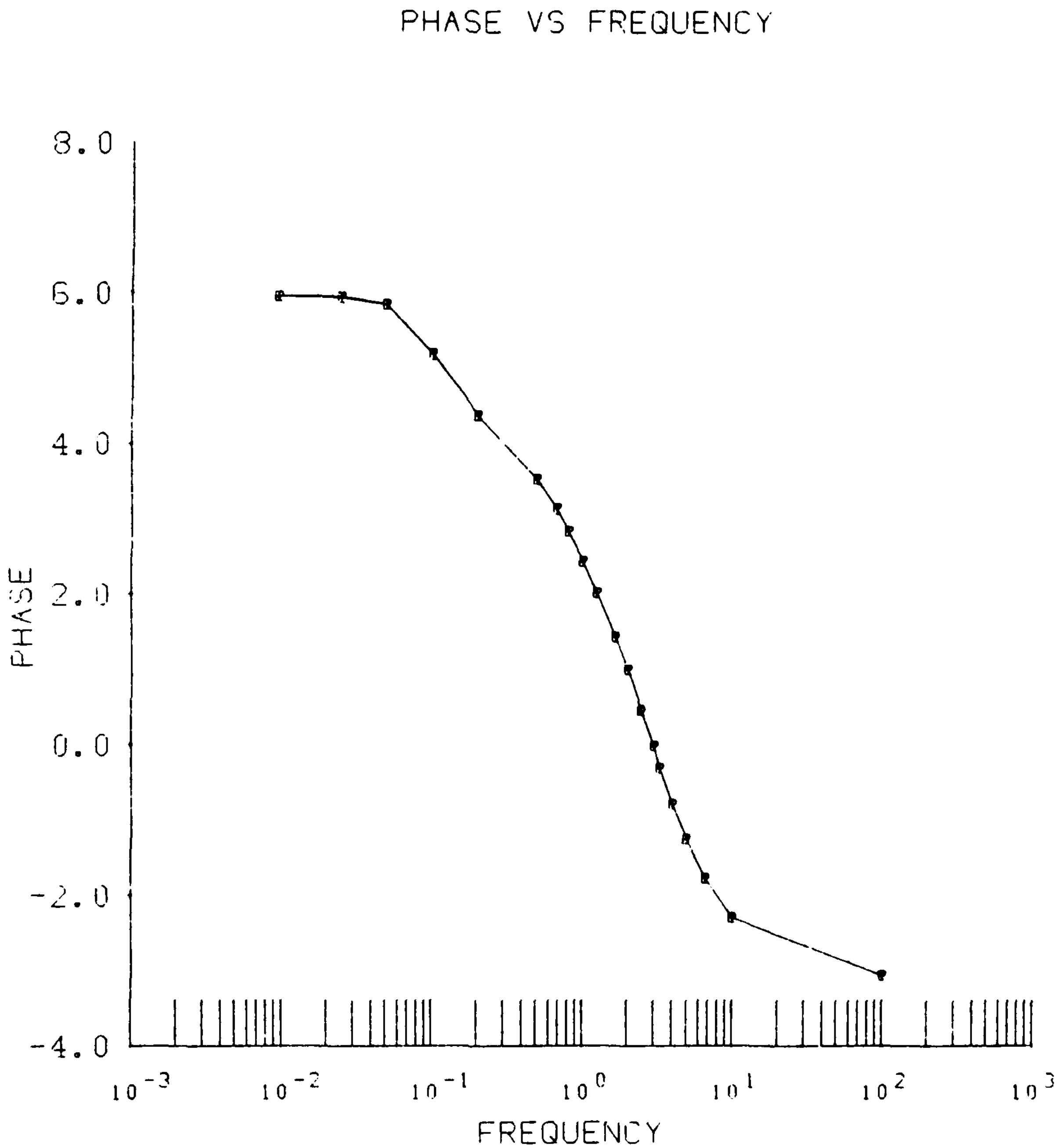

Figure A.4. Phase response of KS36000 seismometer.

APPENDIX B

DECONVOLUTION METHOD

In order to make response spectra from our seismograms, it was necessary to remove the instrument over a certain range of frequencies. In principle, deconvolution simply means dividing the transform of the waveform by the frequency response of the instrument. In practice, this introduces large errors away from the instrument's maximum amplitude due to division by very small numbers. To avoid this problem, we multiply the transform by a causal pseudo-inverse, which is equal to the inverse of the instrument in a frequency band where the inverse can be reliably computed and tapered to zero outside this range. The amplitude response used for the inverse of the Wood-Anderson seismometer is shown in Figure B.1.

The important step is the determination of the phase of the inverse filter. For this we use the technique of Bolduc, et al. (1972). For a causal filter the (log) amplitude and phase are Hilbert transform pairs. The phase of the inverse operator in Figure B.1 is shown in Figure B.2.

Figure B.3 shows application of the deconvolution filter. The deconvolved waveform is smooth and has no acausal phases or abrupt changes. The price paid for this is that the inverse filter is not the true inverse of the instrument response. Figure B.4 shows the waveform after being reconvolved with the true instrument response. The waveform is reassmbled slightly out of phase. Nevertheless, it retains spectral content and the general character of the original waveform.

AMPLITUDE VS FREQUENCY

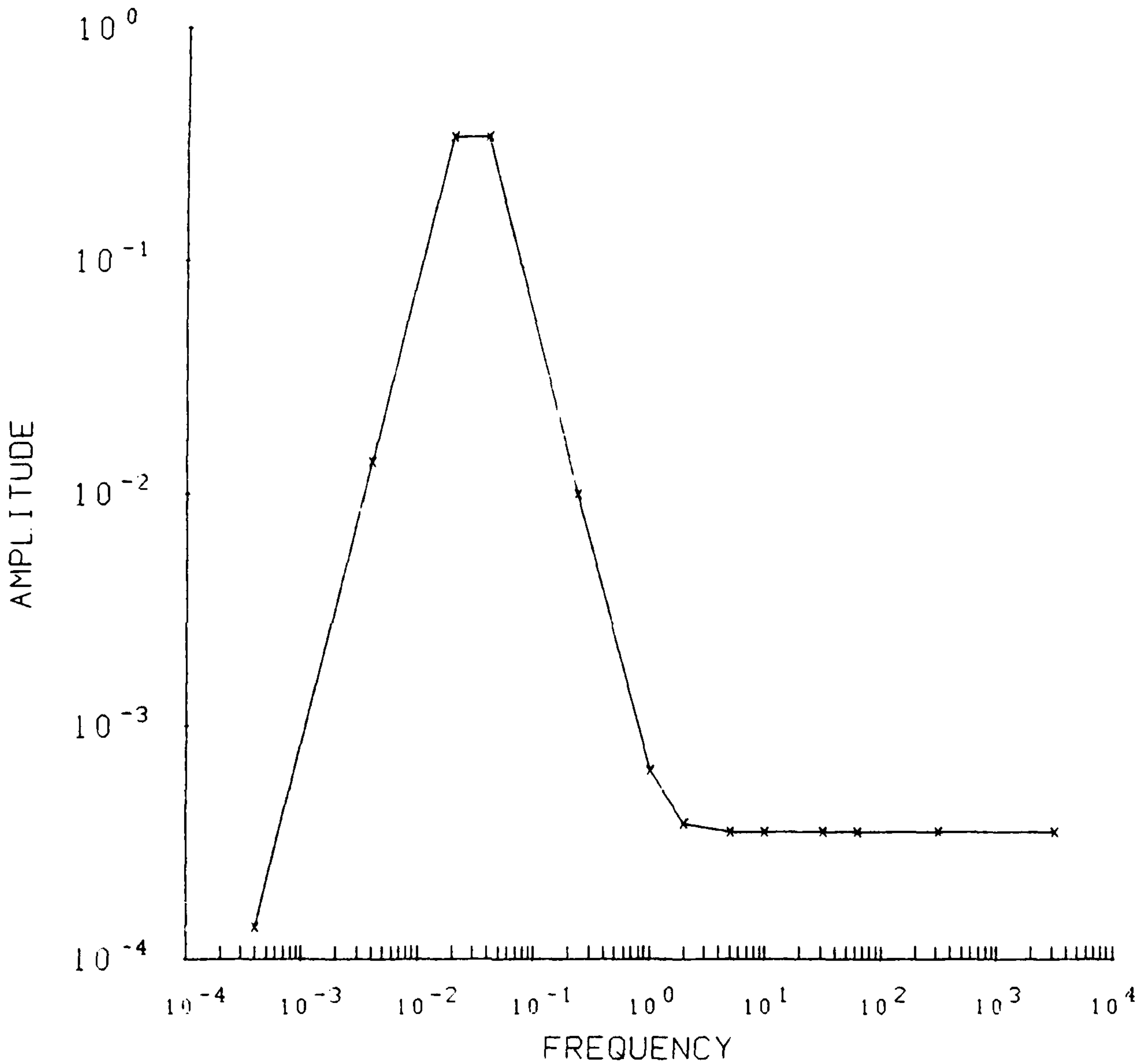

Figure B.1. Pseudo-inverse amplitude of Wood-Anderson seismometer used for deconvolution. The response is exactly the inverse response to a period of 25 seconds and decreases at longer periods.

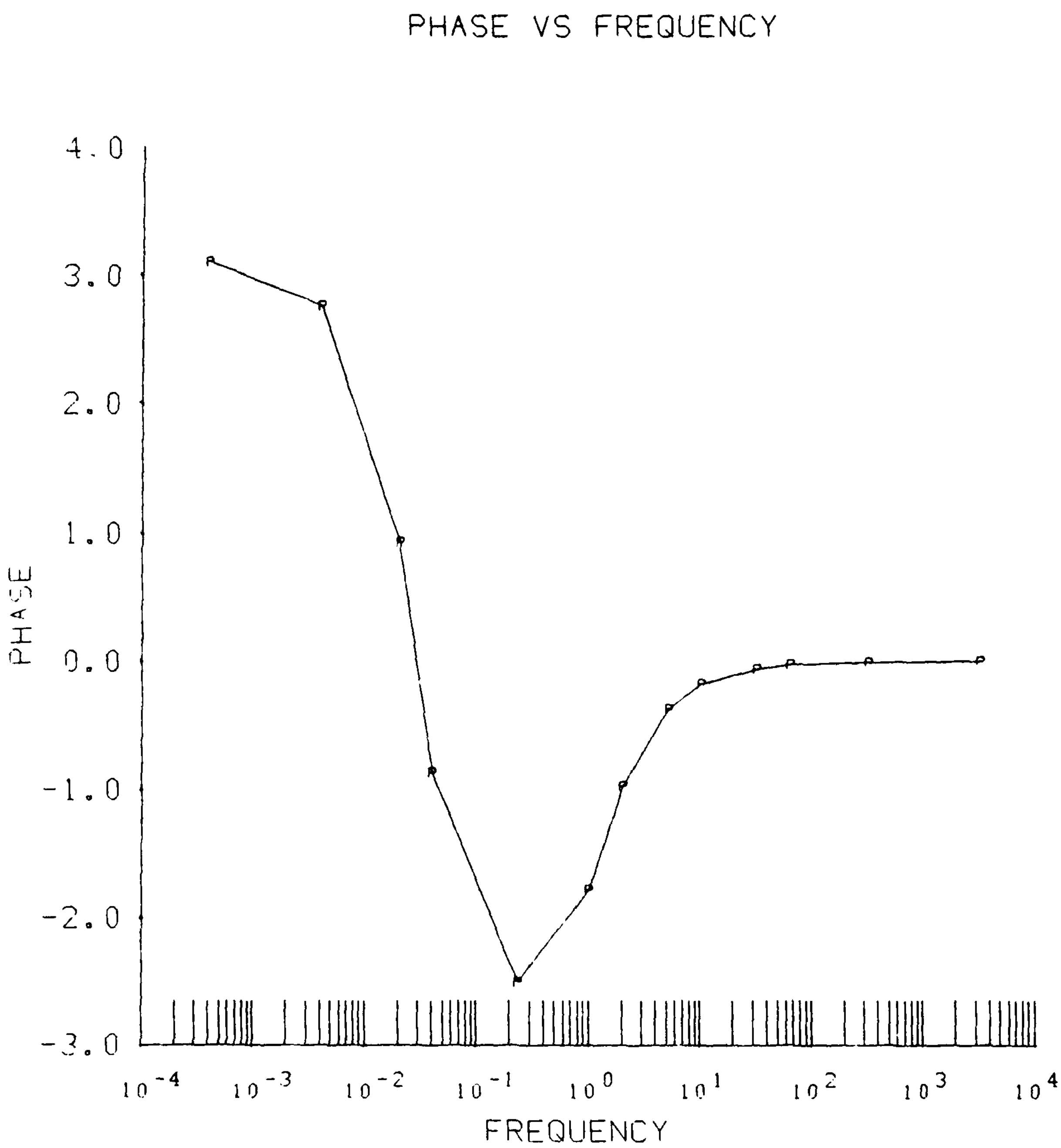

Figure B.2. Phase of the inverse seismometer. This is chosen to be a causal phase and is found by taking the Hilbert transform of Figure B.1.

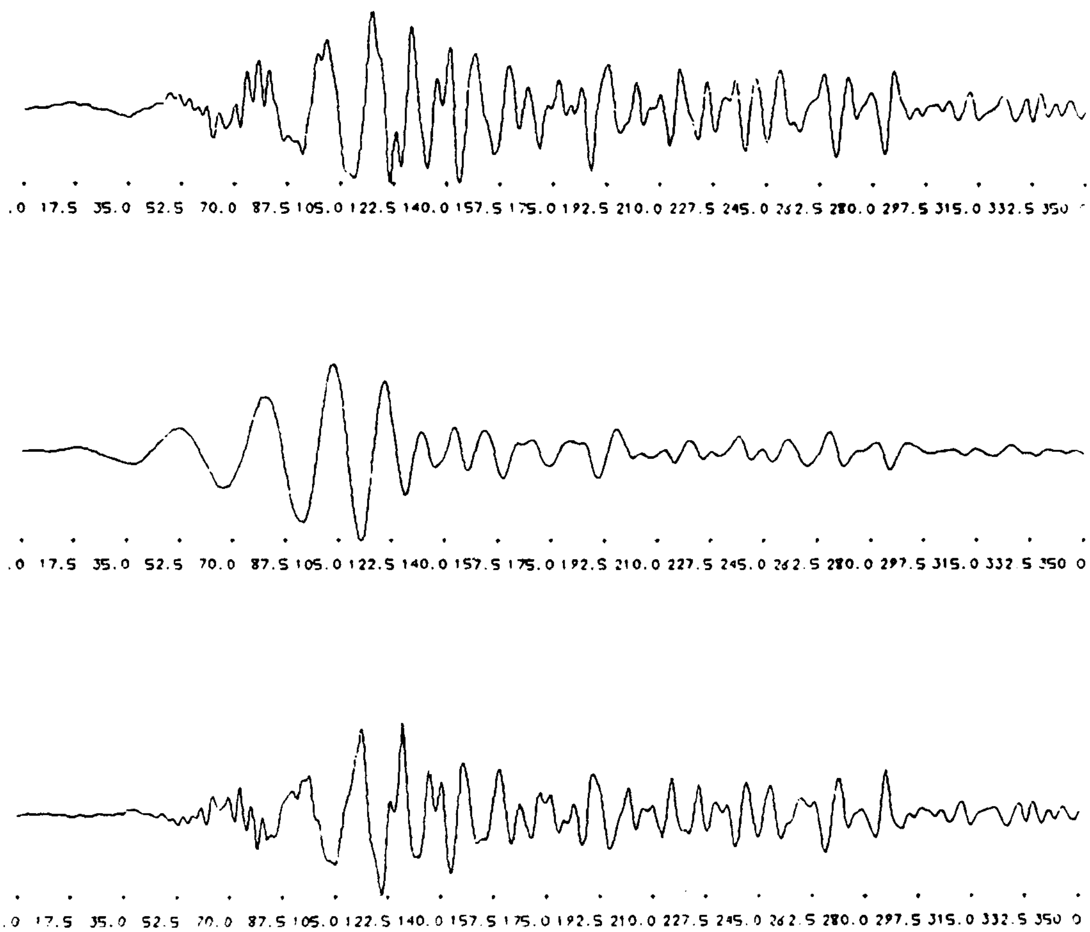

Figure B.3. The top figure is the original Wood-Anderson seismogram, the second is the deconvolved seismogram after application of the pseudo-inverse and the bottom is the reconvolved seismogram made by convolving the Wood-Anderson response with the deconvolved seismogram.

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